research review

OFFICE OF AEROSPACE RESEARCH

OAR: The Research Agency
of The United States Air Force

VOLUME VI NUMBER 4 APRIL 1967

AFOSR Biological Research Directed Toward Reducing Bird-Aircraft Collisions

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BIRD-AIRCRAFT COLLISIONS

The struggle of man with his environment can well be disastrous for an Air Force pilot. On 13 October 1966 a T-37B aircraft operating from Reese AFB, Texas, performed a local weather check enroute to an auxiliary field. Flying at 1,200 feet and 220 knots, the aircraft collided with a large bird which penetrated the windscreen and struck one of the pilots in the head, killing him instantly. In March 1966 a fully loaded C-130 enroute to Vietnam lifted off at McClellan AFB, California. A second later it passed through a flock of starlings crossing the runway. Two of the propjet engines ingested birds and were shut down. The pilot, however, managed to land safely.

These incidents highlight the growing menace of bird-aircraft collisions, which are costing the Air Force up to $10 million each year, numerous injuries and the loss of lives, interruptions of operations, and vast numbers of man-hours required for repair.

BIRD-STRIKE CHARACTERISTICS

Air Force collisions with birds must be reported to the Directorate of Aerospace Safety, Deputy Inspector General for Inspection and Safety, Norton AFB, Calif., when damage is sufficient to classify the occurrence as an aircraft accident. Such collisions numbered 53 in 1962, 70 in 1963, and 145 in 1964. In 1965, and for that year only, all bird strikes had to be reported whether damage resulted or not. The total was 839, nearly 6 times the number for the previous year. The reporting procedure was changed in order to provide a more representative history, and to obtain statistical information of value in current research programs directed at reducing the bird hazard. (1)

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Experience for 1966, not yet tabulated, appears to follow the established trend and to bear out the grim fact that bird-aircraft collisions are increasing in frequency and cost. While separate cost accounting is not presently being performed, there are ample indications to support the $10-million estimate. Seventy-five engines were replaced in 1965 because of bird ingestion. Damage reports cite a constant toll of windscreens, canopies, air intakes, radomes, wing and fuselage panels, flaps and landing gear, and particularly jet engines. The number of man-hours required to repair duck-impact damage on a B-52 wing leading edge, for example, can run as high as 100, indicating severe damage to electrical and other systems. A single bird can reduce a jet engine,

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costing several hundred thousand dollars, to a pile of scrap in an instant, if compressor blades are broken off and sucked farther into the engine.

On the basis of data for 1965, these patterns in bird-strike incidents have been observed: (1) The birds were only infrequently observed prior to impact; and in almost half the incidents the species of bird involved was not identified. Small birds such as blackbirds, starlings, sparrows, and doves were most frequently encountered near airfields. Seagulls, starlings and blackbirds were the most frequently identified species. (2) More strikes involved transport-type aircraft, with trainers second. (3) Most encounters occurred below 1,000 feet, with a quarter of these taking place on the airfields themselves. (4) Out of 839 strike incidents, 138 occurred on airfields, and 243 within one mile of airfields. Of the remainder, 149 occurred during low-level training missions, including radar-evasion, gunnery, and navigation practice runs. (5) There were 109 engine ingestions reported, requiring 26 shutdowns and 75 replacements. Windscreens and canopies were involved in 178 incidents, with 8 penetrations and 4 cases of minor injuries. (6) Out of 694 incidents within the continental United States, 70 per cent took place in the southern half of the country. The highest two-month accident period was September-October, with

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OAR RESEARCH REVIEW is published monthly by the Office of Scientific and Technical Information (RRYC), Hq Office of Aerospace Research, USAF, 1400 Wilson Boulevard, Arlington, Va. 22209. The objective of this publication is to make a positive contribution to the exchange of information concerning Air Force conducted and sponsored research activities.

JACOB SEIDEN
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From the Editor:

In order to broaden the participation of the scientific community in the exchange of information on OAR-sponsored research, we cordially invite all contractors and grantees performing research for OAR to submit articles for publication in the OAR Research Review. Such contributions should be submitted through the contractor's or grantee's OAR project monitor, and will bear the author's by-line. A short biography and photograph of the author may be included, if desired.

Those OAR contractors and grantees interested in contributing articles on their current research to the Review should write to us through their project monitors for the necessary guidelines on the desired format, quality of illustrations required, and other pertinent information.

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March-April the next highest. These periods coincide with bird migrations.

Although the Air Force has a mandatory reporting system, commercial and private aircraft operators may, but are not compelled to, report bird strikes. During 1966, the Federal Aviation Agency was notified of about 650 such strikes. At one time in the recent past, an airliner was downed with the loss of 17 persons when it hit a swan, which caused a stabilizer to fail. Another airliner's engines ingested starlings on takeoff. As a result, the airliner crashed, killing 62 people. U.S. airlines in past years have reported an average of about 300 bird collisions per year. In 1965, as the result of FAA's stress on these

Figure 1. Damage to stabilizer of a T-37 by a bird.

reports, about 650 were filed by U.S. airlines. One Canadian airline has reported that virtually every jet engine in its fleet has ingested birds. (2)

Bird-aircraft collisions are definitely on the increase as aircraft get larger and fly faster, and cover more miles each year. Even graver consequences may be in the offing with extremely large aircraft such as the C-5A transport entering the inventory. Supersonic aircraft add still another dimension to the problem, particularly the F-111 which will fly considerable portions of its missions "on the deck."

COUNTERMEASURES

There are many approaches to the problem. The brute-force method provides birdproof windshields for aircraft ranging from the C-47 to the C-141. These will protect the pilot from strikes of 4-pound birds with the aircraft flying at 500 knots. The supersonic strike is still largely an unresolved problem; but there is no question about what happens when a large bird hits a small aircraft. As yet, no way has been found to birdproof a jet engine without paying a stiff penalty in aerodynamic efficiency.

Another approach suggests that "If you don't see them, they aren't there." This approach may take several forms. For example, there is a reluctance on the part of many who fly to admit the magnitude and, sometimes, even the existence of the bird-aircraft-collision problem. Pilots dislike having to make detailed bird-strike reports. Airlines fear to alarm the public. Base commanders don't care to curtail flying schedules. Traffic controllers are unhappy about having their screens obscured by clouds of migrating birds. Indeed, more than one airport radar has been re-engineered to reduce the return from birds when these unwanted "angels" were found to interfere with aircraft control. And in an age when a barefooted rifleman can bring down a multimillion-dollar aircraft with a single shot, it is sometimes difficult to be concerned about seemingly nonurgent problems.

At one training base, T-37s regularly flew through flocks of blackbirds. These birds occupied a winter roost a few hundred yards from the main runways, with a population estimated at five million. Because of extremely tight training schedules, the toll of engines, windscreens, landing lights, and wing and tail surfaces was accepted for a time. But flying at that base has since been curtailed during the birds' travel from and back to the roost at dawn and at dusk. However, a more important lesson to be derived from this example has to do with the location of air bases. This particular base was built adjoining the roost, which had existed for as long as the oldest residents of the area could remember. And even now, in the New York City area, one of the sites being considered for a possible new jetport is located within a major waterfowl refuge.

Since most bird-strike incidents occur on or near airfields, an effective approach would be to make airfields a less attractive habitat for birds. Standard measures, advocated by both the FAA and the Air Force, include harassment by liquid-propane-fueled noise-makers, shotgun-shell explosive crackers, and recorded bird distress calls. Also, marshes have been drained, herbicides and insecticides have been used, trees and grass have been cut, crows and owls have been trapped, and dumps and other refuse have been eliminated. But these measures have only been partially effective in view of the fact that most airfields are located in areas naturally attractive to birds, such as filled areas near water, agricultural land, and woods and forests.

THE ROLE OF RESEARCH

It appears that the best hope for developing workable, effective solutions to the problem lies in acquiring increased knowledge of the birds themselves. Bird-aircraft collisions will never be prevented entirely so long as aircraft and birds are in the air together; but the probability of having such collisions can be reduced markedly. As with most difficulties arising from man's relationship with his environment, answers can come only from a better understanding of the nature of the problem, and from new knowledge provided by scientific research.

The Life Sciences program of the Air Force Office of Scientific Research (AFOSR), Office of Aerospace Research, has included many studies on bird metabolism, and on such activities as breeding and nesting, feeding, migratory and other movements, and navigation. Other research has been sponsored on species interactions and distributions. This long-standing program provides an interesting example of the relevance of basic research to Air Force operations, and particularly of the role of scientific research in support of a technology-dependent and technology-oriented organization like the Air Force. While bird research has been conducted at relatively modest program levels, the scope has been broad, and has identified the Air Force as an organization providing pivotal support to scientific research concerned with the bird-aircraft-collision problem. This support has also provided AFOSR, through its researchers and membership in interagency committees, with access to the best of current research being carried on by other Federal and state agencies, universities, and private groups. Close co-ordination is effected with other elements of the Air Force through the Special Assistant for Natural Resources Conservation, Deputy Inspector General, who provides scientific liaison for Air Force wildlife management problems.

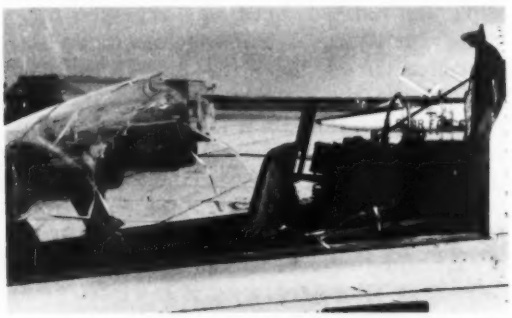

Figure 2. Damage to canopy by a bird.

AFOSR has for eight years supported research by Dr. William J. Hamilton, III at the University of California, Davis, Calif. Dr. Hamilton, generally, is studying the basic biology of the starling; specifically, he is investigating the highly organized social and group activity involved in its flocking, traveling, roosting, feeding, and other activities. An understanding of the entire ecosystem of a given species will make it possible to learn how to manipulate all species more successfully. It may thus be said that the problem of bird-aircraft collisions is ultimately one of bird ecology.

The starling's particular refuging and dispersal activities offer insights into some of the basic mechanisms determining the movements of birds in general. The daily radiative dispersal from the roost is a pattern observed in many animals in which the population occupies a concentrated core area from which it emerges and radiates to nearby feeding areas. Because starlings flock to mutual advantage, they do not aggressively defend space, but concentrate on feeding. The

same bird does not go to the same place each day, but varies the foraging area on the basis of past successes and dietary need.

Starling populations were traced by Dr. Hamilton and his graduate students to a giant roost in California's Sacramento River, from which the birds radiated each day as far as 50 miles, affecting both Travis AFB and McClellan AFB, near Sacramento. This 50-acre roost sheltered two million starlings and about the same number of blackbirds. Checkpoints at 10-mile intervals revealed that concentrations of passing starlings declined gradually up to 50 miles, and then dropped sharply. The starlings were found to adopt deployment strategies designed to use and gain energy efficiently. Birds which fly 50 miles, taking an hour and 40 minutes each way, must seek out more energy sources in the form of food than those which fly only 5 miles. However, the farther out a bird flies, the less competition there is from other birds, and the available food becomes accessible at an increasing rate. This balances the additional expenditure of energy required for the greater distance traveled. Ultimately, when a particular distance is reached, competition ceases, and there is no reason for the birds to go farther. It becomes obvious, then, that a basic understanding of the core (roost) as a very stable, radiative system would be a major step in making it possible to predict biosystem problems that may arise in connection with bird dispersal. It may also make it possible to cope with the difficulties of bird-aircraft collisions in a more effective manner, and to prevent other problems from arising. (3)

Coloration causes the major difference in the heat-absorption capability of all animals. Recent research by Dr. Hamilton and Frank Heppner indicates that an animal's black color may function primarily to promote the absorption of solar energy, thus reducing the expenditure of energy required to maintain body temperature. This would be an important advantage to the starling which must work hard during the day, and seek shelter at night. In an experiment to test this view, the energy expenditure of white zebra finches was measured with and without artificial sunlight. The same birds were then dyed black

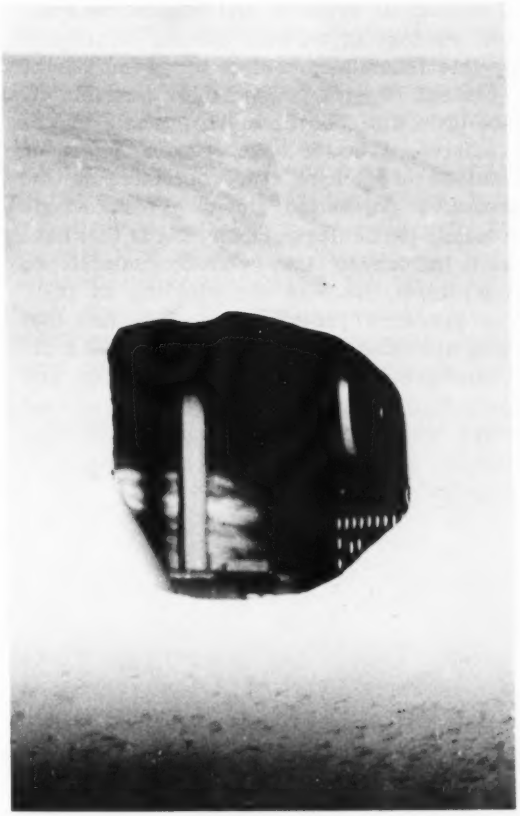

Figure 3. Hole in leading edge of right wing of a B-52G at Loring AFB, Maine. The aircraft hit a duck at 2,000 feet over the arctic.

and compared once more. The dyed birds under light were found to use an average of 20 per cent less energy, by measurement of their oxygen consumption, than when they were white, or when they were of either color and lacked artificial sunlight. This same evidence is applicable to man. Dark skin coloration may increase the absorption of solar radiation in situations where energy must be expended, as at dawn and dusk in otherwise hot climates. (4)

Dr. Hamilton's work also indicates that certain aspects of bird-population dynamics may be approached by computer simulation. These analyses could be based on available extensive banding and recovery data. Such investigations may lead to mathematical models that can deal with the complexity

of ecological systems and suggest the relative wisdom of various control strategies. By this technique, control programs can be evaluated in advance and their possible effect upon the ecosystem as a whole can be predicted. A better understanding has been obtained of factors that contribute to the explosive population growth of a single species, particularly among birds that have been introduced into already established ecosystems, as was the starling in 1890. The research program also indicates that there are other introduced species that could create greater problems for aviation and agriculture than the starling. Increased knowledge is needed to evaluate these species and to identify those factors that could trigger their population growth.

The first Working Conference held by ecologists on research related to the bird-aircraft-collision problem was sponsored by AFOSR, and conducted by Dr. Hamilton at Davis, California, 31 May to 3 June 1966. Attendees included administrators and research scientists viewing the question from the standpoint of the interlocking web of phenomena and processes common to most animals. They agreed that, beyond the study of birds and tactical alterations of the environment must come a vigorous and sustained effort involving long-range analyses of complete ecological systems. Systems analysis, including an interpretation of the role and trends of environmental manipulation by man, should be considered, with special emphasis on the trends of bird

Figure 4. Starlings in flight between pastures where they feed mainly on insects in close proximity to cattle. (Vicinity of Davis, Calif.)

populations that may interact with predicted air-travel operations.

The Conference also recommended that a forecast capability be developed based on studies of the timing and characteristics of bird migration. Radar studies can provide one basis for the analysis of bird movements. Modern data-acquisition and reduction systems are required to permit the monitoring of bird movements on a continental basis. By approaching the problem with weather data, perhaps from satellites, with radar data, and with information from birds that can be monitored directly, it should be possible, through interpretation, to predict the periods of maximum aircraft hazard and the locations and altitudes where they are most likely to occur. (5)

Work also has been supported by AFOSR on the effects of sound on bird flocks. This investigation has been carried out by G. W. Boudreau of Santa Rita Technology, Inc., using flocks of blackbirds. The birds have been observed to become severely disoriented by the sounds of jet engines. Tests were performed using jets and sounds cre-

Figure 5. Dr. William J. Hamilton, III, Assistant Professor of Agricultural Zoology, Univ. of California at Davis, holds marked vulture to be released as part of bird-movement studies supported by the Air Force Office of Scientific Research.

ated in the laboratory from a statistical analysis of recorded jet noise. These tests were observed to divert flocks of blackbirds, causing a string-like flock to break and swirl in a characteristic whirlpool action. Some birds are known to be sensitive to radar emissions as well. Both of these techniques offer a potential for the control of birds.

To stimulate scientific interest in the bird-aircraft-collision problem, as well as public understanding, AFOSR presented an extensive display on the topic at the annual meeting of the American Association for the Advancement of Science, held 26-30 December 1966, in Washington, D.C. The exhibit was seen by a majority of the 8,000 university, Government, and industrial scientists and engineers attending. In addition, there was considerable press, radio and TV coverage. Included in the exhibit were a number of aircraft parts damaged by birds, together with numerous photographs. Subsequently, this display was shown to the RTD(AFSC) laboratory directors at a special briefing held for them on the AFOSR research program. The University of California at Davis has also requested that the display be made available for its annual open house.

A brochure entitled Bird/Aircraft Collisions (6) has been published by AFOSR and provided, both with the exhibit and on request, to a number of organizations. These include the Air Training Command, which is distributing copies of the brochure to each of its bases; the office of the Assistant Surgeon General for Veterinary Services, which is sending copies to each base medical and public-health unit throughout the Air Force; the AFSC F-111 Systems Office; and the National Research Council of Canada. A number of foreign-nation air attachés have also received copies of the brochure.

There appears to be no complete solution to the bird-aircraft-collision problem. All that can be achieved is a statistical solution--a reduced probability that such collisions will occur. In all our approaches to this complex question, we have in fact reached the limits of our knowledge. Before further progress can be made, detailed studies must be accomplished of the biology of species which have become pests and hazards, and of the economics of controls suggested by biological research. What most research has shown thus far is that man can learn to live with the problem if he can minimize it so far as practicable.

The big question mark revolves about the birds themselves. Here, much more data is required, particularly on bird migration. For example, the 1960 Maryland airliner crash was caused by a whistling swan. Yet, according to one researcher, virtually nothing was known before the crash of this bird's migration in the Chesapeake Bay area, and very little has been learned since. Formerly, it was believed that birds followed rather well-defined migratory pathways. Now, there is increasing evidence that birds in general, like aircraft, "fly the weather," taking advantage of winds and pressure fronts, and shifting course to avoid disturbances and unfavorable winds. Thus, migratory-bird flight patterns may well lend themselves to prediction with sufficient biological and weather information.

These are the various facets of a serious and growing Air Force and general-aviation operating problem that today is only beginning to yield to scientific investigation.

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ESTIMATION OF PARAMETERS OF LIFE DISTRIBUTIONS

DR. H. LEON HARTER, Applied Mathematics Research Laboratory, ARL

During the past several years, the author has performed extensive research on the problem of estimating the parameters of statistical distributions. Most of the distributions studied have already been applied to the study of life-test data, and the others have potential applications in this field. Collaborator on much of the above research has been Professor Albert H. Moore of the Air Force Institute of Technology, who is the co-ordinator of the AFIT Graduate Reliability Engineering curriculum. In addition, the author has served as ARL sponsor, and Professor Moore as faculty adviser, for several AFIT M.S. theses in this general area.

At first, the author's efforts were devoted to the use of sample ranges and quasiranges to obtain point and interval estimates of scale parameters (standard deviations) of rectangular (5, 7) and normal (5) populations, and of one- or two-order statistics to obtain point estimates of the parameter(s) of one- or two-parameter negative exponential populations (6). Next, his attention was turned to the development of criteria for best substitute interval estimators and their application to the normal (10) and one-parameter negative exponential (9) populations. This work and some of the basic terminology used in estimation have been summarized in a previous OAR Research Review article (8).

More recently, largely with the collaboration of Professor Moore, attention has been directed to two other facets of the estimation problem. The functional relationships between other populations and the one-parameter negative exponential population, for which estimators based on the one-order statistic and on the first m-order statistics of a sample of size $n \geq m$ were known, have been used to obtain one- and m-order-statistic estimators of the scale parameters of Weibull (13, 24, 25) and Type-II extreme-value (26,27) distributions with known shape parameters, of the location parameter of a Type-I extreme-value distribution (18, 25) with known scale parameter, and of the shape parameters of limited and Pareto distributions (26, 27) with known location parameters.

The second and more extensive research program has been concerned with maximum-likelihood estimators, from doubly censored samples, of the parameters of the following populations: normal (15), three-parameter lognormal (16), three-parameter Weibull (14, 17), three-parameter Gamma (14, 17), four-

Dr. H. Leon Harter, senior scientist and mathematical statistician at the Applied Mathematics Research Laboratory, has been with ARL since 1952. As leader of the mathematical statistics group, he provides broad general direction to research in that area. He has an A.B. from Carthage College, Carthage, Ill. (1940), an A.M. from the University of Illinois, Urbana, Ill. (1941), and a Ph.D. from Purdue University, Lafayette, Ind. (1949). He had previously been a Professor of Physics at Missouri Valley College, and an Assistant Professor of Mathematics at Michigan State University. Dr. Harter is a member of several professional societies, and has written one book and a number of technical reports and journal articles.

parameter generalized Gamma (11, 12), logistic (19), and Type-I extreme-value (20). For each of these populations, a computer program for iterative estimation of the parameters has been written and is available from the author on request. The asymptotic variances and covariances of the maximum-likelihood estimators, for various values of the censoring proportions, have been tabulated for each of these populations. For most of them, Monte Carlo studies have been carried out to check the applicability of the asymptotic variances and covariances in the case of small samples. In most cases it was found that the variances of the estimates were not significantly greater than the values given by the asymptotic formulas, even for small samples (10 to 20). The only exceptions occurred in cases in which a threshold parameter was one of those being estimated. In such cases, the variances of the estimates were much larger than one would predict by use of the asymptotic formulas, even for moderately large samples (50 to 200).

This phenomenon was actually observed for the three-parameter lognormal and three-parameter Weibull populations, and there is reason to believe that it occurs also for the three-parameter Gamma and four-parameter generalized Gamma populations, for which no Monte Carlo studies were conducted because they would have required an excessive amount of computer time. No such difficulties occur when the location parameter is a central value (mean, as in the cases of the normal and logistic populations, or mode, as in the case of the Type-I extreme-value population). Moreover, for these latter populations, the mean-square errors of the maximum-likelihood estimates are significantly smaller than the variances of the best linear unbiased estimators when censoring is strongly asymmetric.

The M.S. theses written by AFIT students in Graduate Reliability Engineering have been devoted to point and interval estimators, from one-order statistic, of the scale parameters of Weibull (29) and Gamma (23) populations with known location and shape parameters and to best linear unbiased estimators, based on ℓ of the first m-order statistics of a sample of size n ($\ell \leq m \leq n$), of the scale parameter and in some cases also of the location parameter of Weibull (3, 4, 28, 31), Gamma (2, 22, 28, 31), lognormal (21), logistic (1, 30), and Type-I extreme-value (30, 32) populations.

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Construction of 328-foot Solar Vacuum Telescope on Schedule

SPACE PHYSICS LABORATORY, AFCRL

Construction of the $3.3 million, 328-foot long, solar vacuum telescope at the Sacramento Peak Solar Observatory site at Sunspot, New Mexico, is meeting the timetable set for its 1968 completion date.

Excavation of the 220-foot underground vertical shaft was begun in April 1966 and was completed last November (see Figure 1).

More than 40 per cent is now concrete-lined (see Figure 2). Construction of the above-ground, 135-foot conical-shaped tower and an adjoining laboratory building will begin this spring.

The new vacuum telescope is based on a design concept by Dr. Richard Dunn of AFCRL's Sacramento Peak Observatory. This telescope, together with existing telescopes and facilities at Sac Peak, will establish the Observatory as one of the leading centers for solar research in the United States. The Observatory is located at an altitude of 9,200 feet, on a site noted for its outstanding conditions for observation.

Two design features of the novel telescope will offer exceptional flexibility and resolution. First, the entire optical system, floating on a pool of mercury, will be installed in a 328-foot tube and, together with its associated instrumentation, will rotate as its tower turret tracks the sun. Second, the optical system and instrumentation will be contained in a vacuum in order to eliminate air turbulence which can degrade the telescope's resolution. This design feature also elimi-

Figure 1. Construction site for AFCRL's 328-foot solar vacuum telescope, showing excavation of the 220-foot vertical shaft (lower right).

nates dust collection on optical surfaces. Vacuum pumps will evacuate the entire optical system to working pressures in about four hours, displacing 17,000 cubic feet.

The Davidson Optronics Corporation of West Covina, California, will provide the optical systems, with the Geo-Space Corporation of Melbourne, Florida, providing the instrumentation and electronics systems for the telescope. Construction of the over-all project is under the supervision of the Army Corps of Engineers.

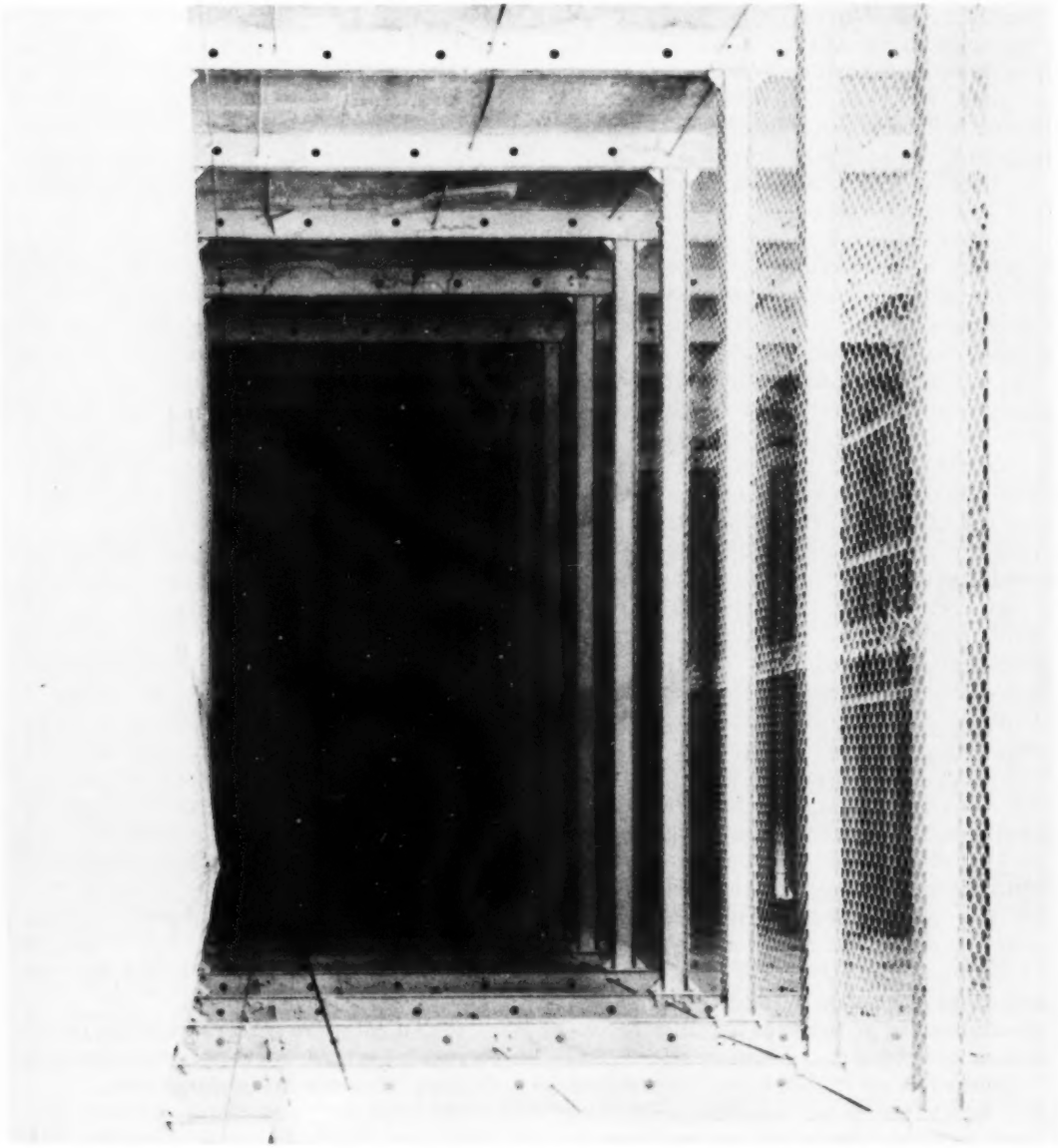

Figure 2. Looking down into the concrete-lined 220-foot vertical shaft of AFCRL's 328-foot solar vacuum telescope. One hundred and thirty-five feet of the telescope's optical system will be situated in the tower, with the remaining 193 feet of the system positioned in the underground shaft. A sump pump and service area will occupy the bottom 28 feet of the shaft.

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KC-135 EXTENSIVELY MODIFIED FOR [redacted] ATMOSPHERIC INFRARED RESEARCH

HERVEY P. GAUVIN and MAJOR WILLIAM F. GRIEDER, Optical Physics Laboratory, AFCRL

Modifications costing about $329,000 are being made to an AFCRL KC-135 aircraft. When these modifications are completed later this year, and new equipment installed, the aircraft will become a unique observation platform for atmospheric infrared research.

AFCRL scientists will use the aircraft to study the production and propagation of visible and infrared energy in the atmosphere. An understanding of these characteristics is of particular importance in the development of Air Force surveillance and reconnaissance systems.

The airborne platform will give AFCRL scientists the mobility to investigate variations in atmospheric properties affecting visible and infrared radiation all over the world. Experiments are planned which will carry the KC-135 from the North to the South Magnetic Pole. Studies are planned in the following areas:

Infrared Aurora and Airglow: This effort will provide data on chemiluminescence, chemical reactions, and reaction rates associated with natural aurora and airglow. Latitudinal and seasonal changes in normal sky backgrounds are of special interest.

Atmospheric Water Vapor: This work will provide statistical data on atmospheric water vapor in the altitude regions of 7 to 12 km and above as a function of latitude, season, and geographic location. Of the many atmospheric constituents, water vapor is the most intense absorber of infrared radiation. The concentration and vertical profile of water vapor have a direct bearing on infrared satellite reconnaissance.

Limited-War Application: Techniques will be evaluated for possible use in low-level detection of infrared targets from an airborne platform.

Project-Equipment Tests: Newly developed or proposed Air Force systems will be tested, evaluated, and refined. One aspect of this work will be the investigation of spectral IR signature data of aircraft, missile plumes, and re-entry vehicles. These studies will be carried out by airborne experiments over a two-to-five-year period. Many of the planned experiments have never been attempted previously.

Nine newly developed instruments will be installed on the aircraft. The new equipment will include: an electronic scan spectrometer, an infrared sky mapper, five Michelson interferometers, and two infrared radiometers.

Conventional supporting instruments to be installed will include a visible spectrometer, a visible sky mapper, a greenline photometer, a filter photometer, and all-sky and documentary cameras.

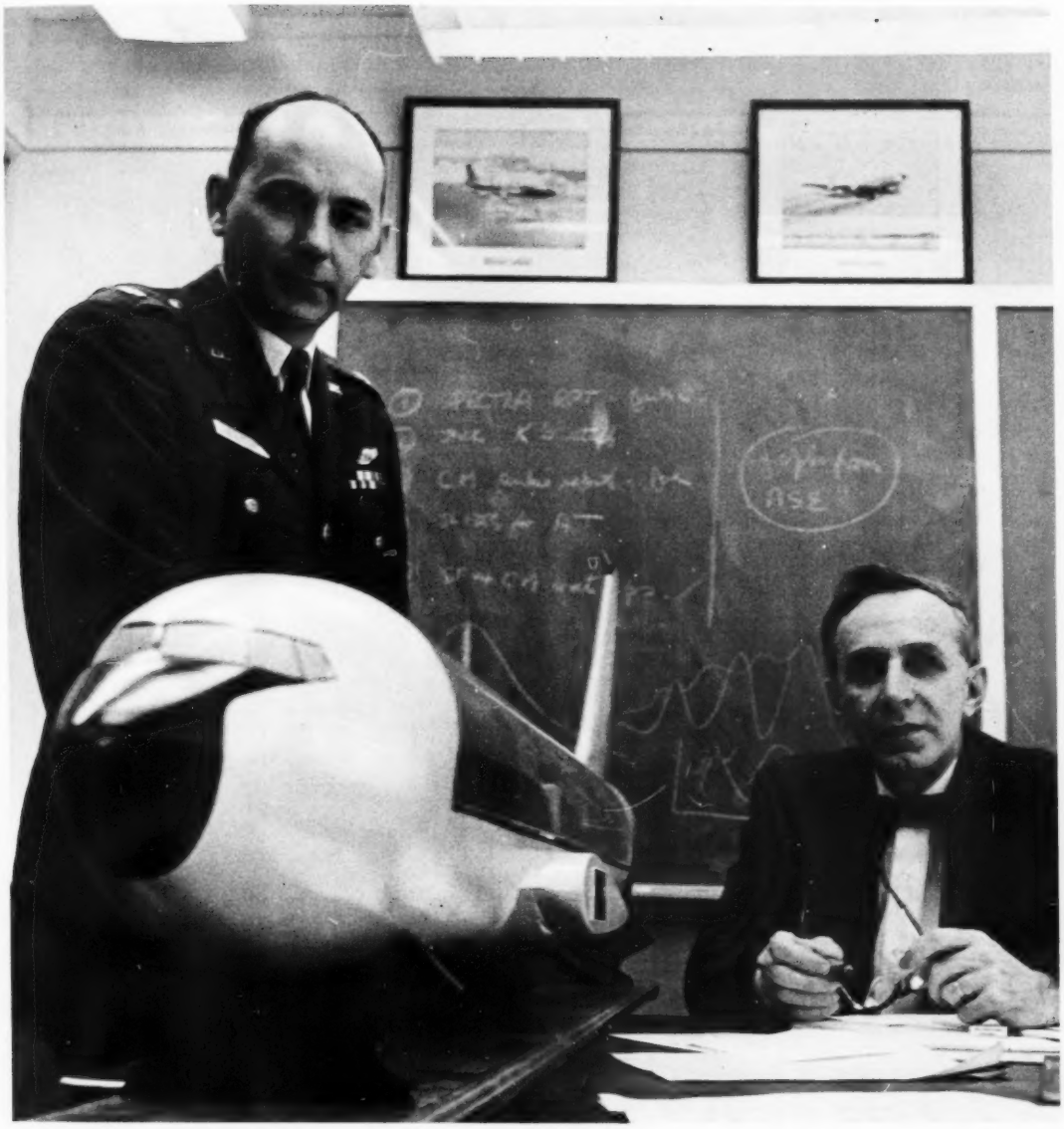
In addition to the equipment above, other specialized instrumentation on the aircraft, listed below, will greatly enhance the overall airborne capability:

(1) A servocontrolled trainable table complex and a trainable periscope to permit simultaneous tracking of seven separate instruments. This feature is particularly valuable when the correlation of data from several instruments is required to accomplish an experiment.

(2) A data-recording complex consisting of five 14-channel analog magnetic-tape recorders and a video magnetic-tape recorder. Features are included to provide necessary timing and indexing for data reduction.

(3) An MD-1 Astro Tracking System for aircraft navigation and positioning in areas lacking adequate navigational aids.

(4) A unique liquid-nitrogen-cooled optical chopper located outside a window of the aircraft. Used in conjunction with a new interferometer system, the chopper permits measurements of extremely low-level infrared sources.



Seated on the right is Mr. Hervey P. Gauvin, Chief, Radiation Effects Branch, Optical Physics Laboratory, AFCRL. Standing beside him is Major William F. Grieder, an electronics engineer in the same Branch.

Mr. Gauvin has been with AFCRL since 1950. During that time he developed a nuclear "bomb-alarm" system now in use by SAC. Currently, he is considering problems related to the effects of high-altitude nuclear detonations on early-warning systems. Mr. Gauvin had previously worked at the Naval Research Laboratory. He has a B.S. in Physics from Brown University (1943), and has taken graduate courses at M.I.T. and Columbia University. He is a member of the American Association for the Advancement of Science, and other professional societies, and has several publications and awards to his credit.

Major Grieder has been with AFCRL since 1964. He serves as Project Officer for a major research program on the optical and infrared effects of nuclear weapons. He had previously been assigned to the Air Defense Command as a jet interceptor pilot. In 1959, Major Grieder received a B.S. in Electrical Engineering and a B.S. in Mechanical Engineering, Aeronautical Option, from North Carolina State College. In 1964, he obtained an M.S. in Astronautics from AFIT. He is a member of Eta Kappa Nu and other professional societies.

BEAD THERMISTOR THERAPY

AEROSPACE INSTRUMENTATION LABORATORY, AFCRL

Temperature-measuring instruments are plagued by systematic errors. But nowhere is this defect more pronounced than in the instruments used to measure temperatures of the upper atmosphere. The accuracy of these instruments degrades rapidly at altitudes above 30 km. The standard temperature curve, for example, that we see drawn on charts with such bold authority represents averages derived from a multitude of measurements over the years.

A common temperature-measuring instrument carried aboard rocketsondes and balloons is the bead thermistor. A thermistor is a semiconductor whose electrical resistance varies with temperature. A bead thermistor is a microscopically small, roundish object only a few mils (thousandths of an inch) in diameter, with electrical connections at each end. In spite of the widespread use of bead thermistors, upper-atmosphere physicists have generally despaired of obtaining acceptable precision from them.

Dr. Donald C. Thompson of MIT, under AFCRL contract, has recently completed a study of bead thermistors resulting in techniques for greatly reducing systematic errors. As a result, bead thermistors may become the most accurate devices to date for measuring upper-atmosphere temperatures. He has analyzed experimentally the many errors these thermistors are subject to, and has established well-defined calibration techniques for the devices. This has led not only to a series of corrective factors to be applied to temperature data over a range of altitudes, but also to improvements in the design of thermistors themselves.

Here are some of the causes of the errors in a bead thermistor carried aboard a rocketsonde. Errors are introduced by aerodynamic heating, by the motion of the rocketsonde through the stream of air, by the influence of the ambient atmosphere on heat transfer, and by simple solar radiation. Other errors are introduced by the conduction of heat from the thermistor supports, by the dynamic responses (lag) of the thermistor itself, and by the measuring current.

When all of these and other errors (most of which tend to result in exaggerated temperature readings) are combined for each five-kilometer-altitude interval, it is shown that, for a 5-mil aluminized thermistor (with a 1.5-cm long lead), the correction factor increases in a roughly exponential fashion from 0.4 degrees C at 30 km, to 23.2 degrees C at 65 km. Of the many factors, the largest single correction must be made for aerodynamic heating.

Dr. Thompson, in his report on the study, remarks that it is unfortunate that a more thorough study of bead-thermistor errors was not made earlier since this would have greatly improved the accuracy of the data from hundreds of past rocketsonde launches.

NEW ANTENNA CONCEPT TO BE TESTED SOON

MICROWAVE PHYSICS LABORATORY, AFCRL

Soon to be tested by AFCRL is a novel antenna covering some 90 acres that may well become the prototype of a new class of antennas. Its geometry (superficially, at least) is simple; it consists of an array of 103 dipoles set roughly in a circle measuring 2,040 feet in diameter. This antenna is being built at Sudbury, Mass.

Antenna designers have not yet settled on an identifying term for antennas falling into this class. Such antennas are variously known as correlation antennas, synthesized arrays, phased-array interferometers, and data-processing antennas. These designations provide clues to the antenna's distinctive features. One feature finds it operating somewhat like an interferometer. The phase and amplitude of a signal reaching pairs of dipoles are compared, and these, in turn, are correlated with the phase and amplitude of signals reaching other dipole pairs. Restoration of target data acquired by the antenna is accomplished by a data processor. The processing of antenna output data permits a great reduction in the antenna collecting area that would otherwise be needed to give comparable resolution. Only the data that is needed is collected, and no more. In the case of the Sudbury array, the 103 dipoles will provide a resolution comparable to that of an array of more than 1,000 dipoles.

High angular resolution provides the basic advantage of the antenna. With processing, this resolution can reach four times that of the Rayleigh criteria which state that, for an antenna with a given aperture and operating frequency, targets must have a certain separation before they are resolved. This high resolution, in turn, carries with it the implication of a greatly enhanced target-discrimination capability--a major Air Force operational goal.

The Sudbury antenna will operate at frequencies between 5 and 7.5 MHz, and will have a 3-degree beam. It will be used only as a receiving antenna. Construction began in the fall of 1966, with first tests planned for the spring of this year. The antenna output data will not be processed on a real-time basis at the Sudbury site, but by AFCRL's digital-computer facility. Scan angle can be changed only by individual adjustments at each of the 103 dipoles, an operation requiring about one hour, with adjustments calculated by the computer. Future antennas, however, could have real-time display and instantaneous beam-switching capabilities. After the performance of the antenna has been evaluated, it will be turned over to AFCRL's Space Physics Laboratory as a permanent radio-astronomy facility.

The Sudbury antenna evolved directly from a number of theoretical studies at AFCRL and elsewhere over the past four or five years. Although these theoretical studies have converged in the Sudbury antenna concept, they were largely carried out as discrete areas of investigation.

A common thread in these studies, however, revolved about particular concepts of communications theory and optical physics which provide novel insights into microwave problems. When viewed in their reflection of a communications-theory problem, antenna and optical systems are similar in the sense that the microwave-antenna and optical-lens systems are both imaging systems in which image quality and resolution are treated as low-pass spatial-frequency filters characterized by a transfer function.

Much of the theoretical work has been concerned with the spatial distribution of electromagnetic energy which bears directly on the optimum configuration of antenna elements. The antenna has a selective response to a spectrum of spatial frequencies--a set of sinusoidal variations in space of specific amplitude and frequency. The antenna response is characterized by a transfer func-

tion. The transfer-function concept, widely used in optics, specifies which spatial-frequency components in the object spectrum will be passed by the antenna, and how much distortion each component will incur as it passes through the system.

The Sudbury antenna layout, which is largely the work of Peter Franchi of AFCRL, is intended to verify theories of imaging and enhancement projected by Dr. Allan C. Schell, also of AFCRL. The transfer-function analysis related to this topic has been carried out by John McIlvenna and Charles J. Drane. In addition to the contributions of these and other AFCRL scientists, the interpretation of antenna imaging in terms of information theory is being done by G. Young and A. Ksienski of the Hughes Aircraft Company under an AFCRL contract.

From left to right are Mr. Peter R. Franchi, Dr. Allan C. Schell, and Mr. John F. McIlvenna, all of the Radiation and Reflection Branch, Microwave Physics Laboratory, AFCRL.

Mr. Franchi, an electronics engineer, is currently working on the improvement and reduction of data from a multiplate antenna, and is investigating complex feeds for large antennas. He received his B.A. in Engineering Sciences from Harvard University in 1959, and his M.S. in Communication Sciences from Northeastern University in 1961.

Dr. Schell has been with AFCRL since 1956 during which time he has worked on phase stable amplifiers, arrays, and microwave antennas. From 1958 to 1960 he served as a lieutenant in the Air Force. He has B.S., M.S. (1956) and Sc.D. (1961) degrees in Electrical Engineering, all from M.I.T. Dr. Schell is a member of Tau Beta Pi, Sigma Xi, and RESA.

Mr. McIlvenna received his B.S. in Electrical Engineering from M.I.T. in 1962, and is presently studying for his Master's degree. Currently, he is working on the application of communication- and information-theory techniques to the design of microwave antennas. He has several publications to his credit.

AFCRL LARYNGEAL CANCER-DETECTION TECHNIQUE BEING EVALUATED BY U.S. PUBLIC HEALTH SERVICES

DATA SCIENCES LABORATORY, AFCRL

A technique for detecting cancer and polyps in the larynx by analyzing human-speech signals was demonstrated several years ago (1961-1963) in research performed at AFCRL by Dr. Philip Lieberman and Dr. William R. Smith (now at Xerox). At that time, co-operative studies were carried out with the Washington Hospital Center, Massachusetts General Hospital, the Boston City Hospital, and other medical institutions. But, because AFCRL's primary interest was in the mechanism of speech production and not in pathology, the AFCRL study was discontinued soon after the technique had reached the point of demonstrated feasibility. Now, however, the U.S. Public Health Service is considering supporting a project based on the Lieberman-Smith research, in which case AFCRL would be called upon to advise on the project.

The research was initially directed at isolating some of the information-bearing elements of speech under a program con-

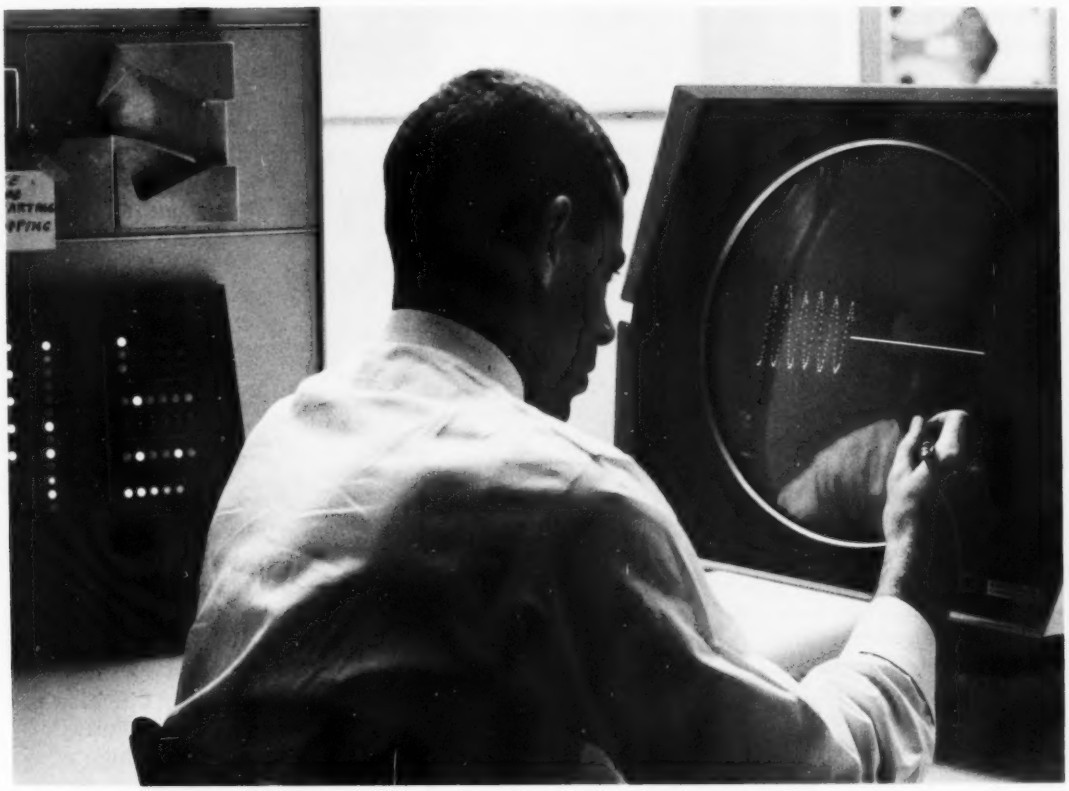


Figure 1. Dr. Philip Lieberman of AFCRL is shown before a computer scope on which is displayed a voice signal of a given uniform pitch. If small tumors or polyps are located on the vocal cords or within the vocal tract, the periodicity of the pitch wave form will be altered. It is this variation in periodicity which provides clues to the possible existence of tumors or polyps in the vocal tract.

cerned with Air Force voice-communications systems. The study involved an analysis of the wave forms of human speech by computer--specifically, the wave form concerned with the pitch component of speech (See Fig. 1). The pitch or fundamental frequency of phonation is generated by the vibrating motion of the vocal cords, which consist of two membranes. The vibratory movements of the vocal cords are regulated by the air pressure against them, and the tensions of the laryngeal muscles. Even with normal speakers, variations in pitch periodicity occur because of small transients in air pressure. However, growths or polyps on or near the vocal cords increase the relative mass of the cords. The system's mechanical damping factor is thus reduced, and air-pressure transients result in larger and more prolonged variations in pitch periodicity than is the case for normal speakers.

During AFCRL's active investigation of the diagnostic technique, the experiments consisted of the analysis of the wave forms of taped voices of patients with known diseased larynxes. The processing of the wave forms involved several steps. First, they were displayed on an oscilloscope and photographed with an oscillographic-record camera. The processed 35-mm film was then read by a computer and the duration of each pitch period was measured automatically. A normalized integral of all pitch perturbations was established for each speaker and plotted. The plots, even for speakers with relatively small masses on or near the vocal cords, showed a marked departure from the plots of normal controls.

As a diagnostic tool, it is envisioned that taped recordings of a speaker suspected of having a diseased larynx could be sent to a central processing center where an automatic analysis of the wave form would be made. The analysis could be made with a specialized apparatus, obviating the need for a large computer. Cost of the wave-form analysis could be reduced to less than a dollar for each examination.

HIGH-POWER GaAs LASERS
with 15 percent efficiency

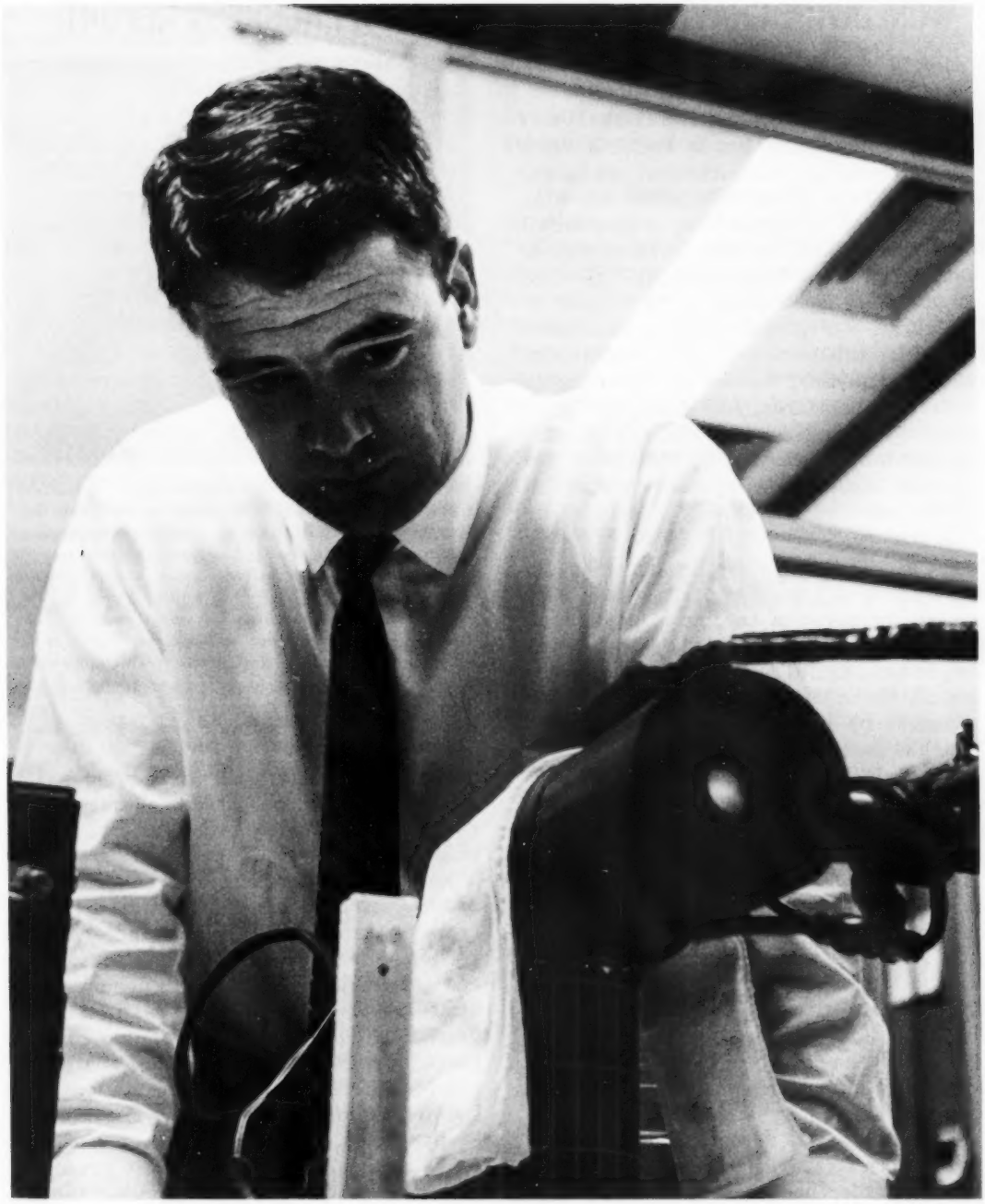
SOLID STATE SCIENCES LABORATORY, AFCRL

Gallium-arsenide-injection lasers with efficiencies of 15 per cent and 3-watt continuous-wave (CW) output have been fabricated and tested by AFCRL and Northeastern University scientists. This represents a threefold increase in power, and a 100-per-cent improvement in efficiency over the best previously reported GaAs lasers. Output measurements were made from the front face of the diode at liquid-nitrogen temperatures.

The CW lasers were fabricated by diffusing zinc into n-type (4×10^{18} atoms/cm) GaAs to form a junction 5 to 8 microns deep. After initial diffusion, the zinc source was removed and the GaAs was subjected to another diffusion for 2 hours at an elevated temperature of 1,000 degrees C. Since there was no source of zinc present during this second diffusion, the junction moved less than 1 micron. But, without the long second diffusion, the junction would not lase.

The work above was carried out by J. E. Ludman of AFCRL and K. M. Hergenrother of Northeastern University. They found that a third diffusion with a zinc source present could be used to create a deeper junction, if desired, but that this third diffusion had little effect on the high output and low threshold of the device. The critical step in the fabrication was the unquestionably long diffusion at 1,000 degrees C. The role of these diffusion steps in achieving high power and high efficiency is not completely understood and is undergoing further study.

CW lasers have potential application in range- and height-finding devices and in communications.



Mr. Jacques E. Ludman, a research physicist with the Device Physics Branch, Solid State Sciences Laboratory, AFCRL, is currently planning and conducting research in the field of solid-state lasers and thin-film measurement to extend and develop the properties of new semiconductors and laser materials. He has been with AFCRL since 1959. Mr. Ludman has a B.A. degree from Middlebury College, Middlebury, Vt. (1956), and an M.S. degree from Worcester Polytechnic Institute, Worcester, Mass. (1958). He has also done graduate work toward a Ph.D. at the University of Pennsylvania, Philadelphia, Pa. He is a member of Sigma Xi.

WORLDWIDE GRAVITY MEASUREMENTS: A PROGRESS REPORT

TERRESTRIAL SCIENCES LABORATORY,
AFCRL

In September 1962, the International Gravity Commission met in Paris. It was a historic meeting. Its conclusions can be reconstructed somewhat along the following lines: "We've been measuring gravity for all these years, and we still have no way of comparing measurements made at Paris with, for example, those made at Washington or Melbourne. We've used different calibration standards, different kinds of instruments, and different analytical methods. Let's now agree on uniform standards, plan a concerted program, and make a fresh start. Let's examine our past work against these standards and see what past results we will preserve, what can be reinterpreted and salvaged, and what we must discard."

AFCRL had taken the initiative at the Paris meeting in seeking such a program, and was prepared to become a major contributor. A highlight of the Paris meeting was, in fact, AFCRL's C-130 gravity-survey aircraft which had been flown to Paris for inspection by the Commission's members. Since the meeting, much progress has been made. Bela Szabo, who directs AFCRL's gravity surveys, has recently reported on the status of the Worldwide Gravity Measurements Program.

Before we look at what's been done during the past four years, let's look at why geodesists have lagged in establishing a worldwide gravity system. Part of the problem was the lack of a uniform reference value. When this situation exists, the obvious solution is to arbitrarily designate a common reference value. If there is a "Greenwich" for gravity measurements, it is at Potsdam where as long as 50 years ago the absolute value of gravity was measured with a pendulum. Modern measurements indicate that the "Potsdam reference" is in error by a negative 11 to 17 milligals. The desired accuracy is about one milligal or less.

The critical problem was the lack of uniform calibration standards for calibration of gravimeters, and the lack of a worldwide

Mr. Bela Szabo, Chief, Gravity Branch, Terrestrial Sciences Laboratory, AFCRL, received his Dipl. Ing. from the University of Budapest in 1938. In his present position, Mr. Szabo directs basic and applied research on the external gravity field of the earth and in the area of physical geodesy. This work includes theoretical research, mathematical methods, measuring instruments and observation techniques. Results of the research are applied to improve gravity-dependent earth constants and geodetic parameters. Mr. Szabo is also concerned with research on the effect and use of gravity for inertial navigation and space programs.

network of base stations (first-order world gravity net) for the purpose of integrating various local gravity measurements into a single uniform system.

For the establishment of a uniform calibration standard and first-order net, two types of instruments are used in worldwide relative measurements--relative pendulums and gravimeters. Gravimeters can measure small gravity differences with high accuracy provided the instruments are calibrated on a gravity range (calibration line) where the gravity differences between the stations are known from higher-order surveys. The calibration lines, having a range of 4,000 to 6,000 milligals, are established by high-precision pendulum and gravimeter measurements. Relative pendulums are used to measure large gravity intervals (about 500 milligals) along the line; the number of intermediate stations between the pendulum sites is increased by groups of high-precision

gravimeters utilizing special measuring techniques. The obtained relative differences between the calibration stations are then used for the calibration of other gravimeters.

Under the worldwide standardization program that began in September 1962, three standardization or calibration lines were established: (a) the Euro-African line, extending between Hammerfest (Norway) and Cape Town (South Africa); (b) the American line, between Point Barrow (Alaska) and La Paz (Bolivia); and (c) the West Pacific line, from Fairbanks (Alaska) to Melbourne (Australia). The principal stations along the three calibration lines are connected by horizontal (east-west) gravimeter measurements providing a network of base stations called the first-order world gravity net. With the exception of some measurements required for verification along the West Pacific line, the standardization work is completed and the gravimeter measurements for the first-order net are in progress. The completed network will consist of only 36 to 40 first-order stations. Any one of these stations distributed over the continents will provide a relative reference for the regional and, in turn, detailed gravity surveys of each respective area.

The last aspect of the program will involve area surveys, using carefully and uniformly calibrated gravimeters, and base stations established by higher-order surveys. This method, known as terrestrial gravimetry, is feasible over economically well-developed areas. But over inaccessible land area (mountains, deserts, etc.) and over the oceans, the conventional terrestrial gravimetry is useless. AFCRL has developed and successfully tested in a KC-135 aircraft an airborne gravity-measuring system which is capable of measuring gravity over areas inaccessible to surveys by any other method.

QUANTUM ORGANIC CHEMISTRY

DR. ANTHONY J. MATUSZKO, Directorate of Chemical Sciences, AFOSR

In theory, at least, all of chemistry is contained exactly within the mathematical formulation of quantum mechanics. This would seem to leave very little for the experimental chemist to do other than to gather data fed from a computer to run his reactions and determine the structures of reaction products. However, except for the simplest molecules, the application of mathematics to solve practical problems in chemistry is often so hopelessly complex that the mathematical expressions needed for exact calculations from first principles (ab initio calculations) are unsolvable even with the most advanced computers. This is especially true in organic chemistry because of the variety and complexity of organic compounds and reactions.

Molecular orbital (MO) theory is a way of applying to molecular structure the ideas and equations of quantum mechanics. (Dr. Robert Mulliken, an AFOSR-supported investigator from 1952-8, was awarded the 1966 Nobel Prize in chemistry for his pioneering work in the development of this theory.) Essentially, the theory regards the electrons of a molecule as being spread out in electronic-wave functions or "orbitals" over the atoms in a chemical bond, or even over all of the atoms of the molecule. These are the electrons that determine the spatial structure, chemical binding energies, ionization potentials, and spectra or light absorption of a molecule.

The theory has been developed to various levels of sophistication. The most elementary form, the Hückel Molecular Orbital (HMO) Theory, is the simplest quantum mechanical approximation that can be applied to understanding and predicting organic chemistry. The most commonly used approach has been to approximate molecular orbitals as Linear Combinations of Atomic Orbitals (LCAO). One of the leading researchers in this area for the past 10 years has been Dr. Andrew Streitwieser at the University of California (Berkeley). With support from the Directorate of Chemical Sciences, AFOSR, Dr. Streitwieser has been investigating the usefulness

and determining the shortcomings of the HMO Theory for groups of organic chemical systems. (In the preface to his book, Molecular Orbital Theory for Organic Chemists, published in 1961 by John Wiley & Sons, Dr. Streitwieser acknowledges AFOSR support). He has taken complex and noncalculable portions of the mathematics and treated them as experimentally determined empirical parameters.

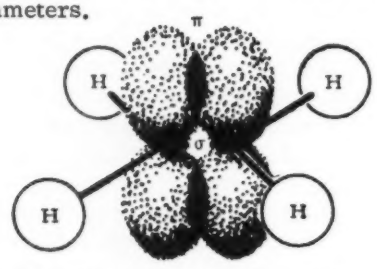
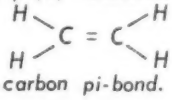


Figure 1. Illustration showing pi(π) - electron charge clouds in  *forming a carbon-to-carbon pi-bond.*

Streitwieser and his research group have been concerned largely with hydrocarbon pi-electronic systems (in which the electron charge cloud is concentrated on either side of the molecular plane as shown in Fig. 1) in order to provide a thorough test of the ranges and limitations of application of molecular orbital theories. They limited their initial studies to hydrocarbons since each atom other than carbon in the pi-system would introduce new parameters. The research was aimed at providing experimental data on hydrocarbon systems including carbonium ions and carbanions suitable for the thorough testing of applications involving pi-electronic energies.

In his early work, Dr. Streitwieser examined the ionization potentials of a number of organic compounds (ionization potential is the energy necessary to remove an electron from a compound in the gaseous state). The organic cations obtained by such electron removal are important in many reactions involving organic compounds under extreme conditions. Streitwieser found that a modification of the original HMO Theory gave excellent results in correlating the ionization potentials of many molecules. He called this modification the "omega technique" since a proportionality or "ω" term was introduced into the quantum mechanical expressions to account for electron repulsion. The values determined experimentally were found to be in close agreement with theoretical predictions.

The study of the effect of structure on the acid properties of molecules has always been an important part of theoretical organic chemistry. Very little data was available on compounds having the extremely low acidity characteristic of most hydrocarbons. Streitwieser and his co-workers found the available data correlated nicely with predictions of molecular orbital theory. However, even this data was only semiquantitative in nature. Dr. Streitwieser set out to obtain experimental quantitative measures of the relative acidities of such very weak acids. His general technique involved following the rate of removal of a hydrogen isotope (deuterium or tritium) from a hydrocarbon with the use of a strong base, the lithium or cesium salt of an organic amine. Special techniques were developed because the reactions had to be carried out in vacuum line systems. An extensive set of results was obtained on the relative stabilities of carbanions of the benzyl, polyarylmethyl, aryl, fluorenyl, and other hydrocarbon systems for application of MO Theory. It was found, for example, that the poor results given by MO Theory in these cases is due in part to a neglect of inductive field effects (the effect of substituent groups on the rest of the molecule.) This research is now yielding quantitative measures of hydrocarbon acidities ranging from hydrocarbons with such low acidity as alkanes to those with acidities comparable to those of alcohols. In the process of doing this research, a great deal was learned about the nature and chemistry of alkali-metal organic compounds in amine solvents. Consequently, in addition to the original aims of the investigation, these results have become germane to the chemistry of anionic polymerization, a technique that has become increasingly important in technology.

Although simple Hűckel MO approximations are in many cases woefully inadequate,

they have formed the foundation for more accurate calculations and predictions of organic chemical structure and reactivity. Dr. Streitwieser's modifications by way of the omega technique have been very effective when applied to certain systems. He and other researchers, as, e.g., AFOSR investigator Dr. Michael Dewar at the University of Texas, are looking into more sophisticated approaches to quantum organic chemistry. Applications of self-consistent field molecular orbital (SCF MO) methods are now in progress in both laboratories. Dr. Dewar is including in his studies the calculations of heterocyclic systems (where a noncarbon atom is present with the carbons in a ring). The Air Force benefits from this research in quantum organic chemistry and, as more and more useful theoretical information is obtained, it will make possible the synthesis of many novel materials so necessary for the various Air Force applications.

BLOCK THAT PASS (ENERGY TRANSFER BY PHOTOSENSITIZERS)

DR. ALFRED WEISSLER,
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On U.S. military bases around the world, a crescendo of excitement builds up each fall with the approach of the Army-Navy football game. Only the Air Force components manage to maintain a nonpartisan calm when a forward pass is blocked or completed.

Another kind of pass draws a great deal of attention at AFOSR--the hand-off of excitation energy from one molecule to another. Several investigators are being supported in their studies of this process, which is important in such varied fields as that of sonic boom, the deterioration of materials in the aerospace environment, and propulsion, i.e., the effort to squeeze out extra thrust from a jet engine's exhaust gases.

Dr. George S. Hammond, a distinguished worker in this area at Cal Tech, has been studying, with AFOSR support, the ways in which light energy can be absorbed by a photosensitizer molecule in solution, retained briefly in a metastable triplet state, and then passed along to another type of molecule in the solution to cause a chemical transformation. One interesting system uses a photosensitizer which is "optically active" (i.e., rotates the plane of polarized light) to give a photochemical reaction product which is also optically active. The kind of sensitizer employed is a derivative of naphthalene, as shown in Fig. 1. The photochemical reaction involved the stereoisomerization of trans-1, 2-diphenylcyclopropane (Fig. 2) into the cis form. Even though the starting trans material was a racemic (non-"active") mixture of the dextrorotatory (clockwise) and levorotatory (counterclockwise) forms, the solution developed optical activity as the reaction proceeded, to an extent paralleling the amount of conversion to the cis isomer.

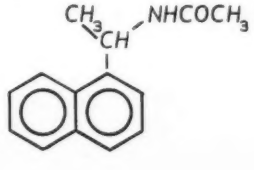

Figure 1.

Naphthalene-type photosensitizer.

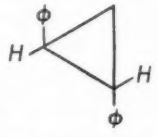

Figure 2.

Trans-1, 2-diphenylcyclopropane.

From these and other experiments Dr. Hammond concluded that, (unlike football!), there must be actual contact between the passer and the receiver molecules, and that an optically active passer of energy shows a preference between the dextro and levo types in a mixture of possible receivers. Apparently, particular donor-acceptor orientations are required for efficient energy transfer, and these are restricted by the shapes of the molecules involved. Six different naphthalene-based sensitizers have already been studied, revealing interesting variations in the selectivity. Although there is no simple explanation yet in terms of the size or polarity of the photosensitizer molecule, the results here and in a host of related investigations are giving the Air Force the power to "block that pass" in the important area of energy transfer from molecule to molecule.

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U. S. GOVERNMENT PRINTING OFFICE : 1967 O - 261-718

925-047